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LHCb physics performance

P. Koppenburg
on behalf of the LHCb collaboration

Institut de Physique des Hautes Energies, Université de Lausanne, Switzerland
e-mail: Patrick.Koppenburg@cern.ch

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Abstract. The LHCb physics performance is presented with emphasis on the impact that LHCb can have on the determination of the CKM unitarity triangle.

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1 Introduction

CP violation arises naturally in the electroweak theory as a complex phase in the quark mixing matrix [1] but is very weakly constrained experimentally. It is well established in the neutral kaon system but has only recently been observed in the B meson system by the BABAR and *Belle* collaborations [2, 3].

The CKM quark mixing matrix exhibits a strong hierarchy of its elements. The unitarity of this matrix can be expressed as six orthogonality relations which can be drawn as triangles in the complex plane. The triangles that govern kaon decays are squashed because of this hierarchy and consequently CP violation is very small in this sector. On the other hand the two triangles that govern B physics are not squashed. They are sketched in Figure 1. The B meson system is thus the best laboratory for CP violation studies, as many asymmetries are expected to be large.

To understand CP violation and the hierarchy of masses in the Standard Model (SM) it is necessary to measure all angles and sides of these triangles. Furthermore New Physics is not expected to be CP conserving and would generate inconsistencies in the CKM picture. There are indications from cosmology that the amount of CP violation accounted for by the SM is far below what is needed by the baryogenesis process that is responsible for our matter–antimatter asymmetric universe.

So far, the only clear evidence of CP violation in B decays is the measurement of the non-zero value of $\sin 2\beta$ [2, 3]. By the start of the LHC in 2006 the following parameters of the CKM unitarity triangle are expected to have been measured:

- The combined precision from BABAR, *Belle* and the Tevatron Run II on $\sin 2\beta$ may reach 0.03.
- The CDF and DØ experiments will have measured Δm_{s}. The resulting precision on the $|V_{\mathrm{td}}|/|V_{\mathrm{ts}}|$ ratio (which constrains the length of the side opposite to γ) will probably be limited by theoretical uncertainties.

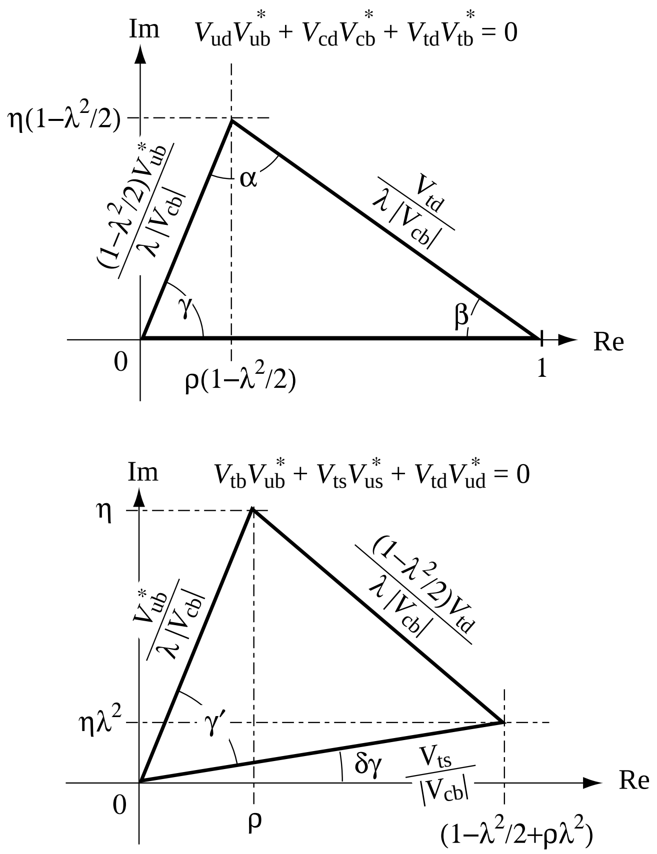

Fig. 1. The two non squashed unitarity triangles. The upper one is usually called “the” unitarity triangle. V_{ij} are the matrix elements of the CKM matrix and λ, η, ρ parameters used in Wolfenstein’s parameterization [4].

- The other side (opposite to β) will be constrained by the ratio $|V_{\mathrm{ub}}|/|V_{\mathrm{cb}}|$ obtained from b → c and b → u transitions. Theoretical uncertainties will also limit the precision on this ratio.

Although these constraints will allow to construct the triangle, the system will not be over-constrained and may thus not reveal an inconsistency, even in presence of New Physics. To draw a complete picture, CP violation has to be studied at a high precision level using the full spectrum of B hadron decays.

2 The LHCb experiment

The LHCb experiment will use the full potential of the LHC for dedicated CP violation studies in the B sector. The assumed $\mathrm{b}\bar{\mathrm{b}}$ cross-section of 500 μb at

14 TeV and a luminosity of $2 \cdot 10^{32}$ cm^{-2}s^{-1} (optimized for physics performed with events containing single proton-proton interactions) lead to a total of 10^{12} $\mathrm{b\bar{b}}$ pairs per year (10^7 s).

The apparatus is described elsewhere in these proceedings [5] and in recent Technical Design Reports [6, 7, 8, 9, 10, 11, 12]. Its key features are:

Forward geometry: Both b hadrons are produced in a correlated manner either in the positive or negative direction. With the spectrometer acceptance of 10–300 mrad a large fraction of B decays and the tagging lepton or kaon from the other b-hadron are fully contained in the acceptance.

Dedicated trigger: A dedicated first level trigger based on modest p_T requirements for leptons, photons and hadrons allows to select efficiently leptonic and hadronic B decays [13, 14]. The second level topology trigger uses the high precision vertex locator to find detached secondary vertices [15].

Hadron identification: The two RICH detectors [16, 9] provide together a K/π separation better than 3σ over the momentum range 2–100 GeV. This allows the efficient selection of decay channels like for instance $\mathrm{B} \to \pi\pi$ which has a much lower branching ratio than decays with the same topology as $\mathrm{B} \to \mathrm{K}\pi$ or $\mathrm{B_s} \to \mathrm{KK}$.

Good resolution: The vertex locator and tracking system reach a typical resolution of 12 MeV on the B mass, which is useful for background rejection [17]. The resolution on the B proper time is about 40 fs, allowing to resolve the short oscillation period of the $\mathrm{B_s}$.

2.1 Systematics

In a precision experiment like LHCb it is very important to track all sources of systematic errors. Charge-dependent detector efficiencies could for instance mimic CP violation by biasing the reconstruction or tagging efficiencies. As the vertical magnetic field deviates the charged particles to either side of the detector, left-right asymmetric efficiencies could cause such an effect. Also the asymmetry in the b and $\mathrm{\bar{b}}$ quark production rates that is expected at a pp collider can mimic CP violation.

Charge-dependent efficiencies can be identified and corrected for by swapping the polarity of the dipole magnet. The choice of a warm magnet allows a frequent change of the polarity. LHCb foresees also the use of large control samples where no CP violation is expected. 600k $\mathrm{B_d} \to \mathrm{J}/\psi\mathrm{K}^*$, 600k $\mathrm{B_u} \to \mathrm{J}/\psi\mathrm{K}^{\pm}$ and 86k $\mathrm{B_s} \to \mathrm{D_s}\pi$ decays will be recorded per year for this use.

3 Overview of benchmark channels

In this section we briefly review the most important measurements of the CKM triangle parameters. All yields are given for one year of data taking (10^7 s) at nominal luminosity, corresponding to an integrated luminosity of 2 fb^{-1}. We do not go into the details of the event selection and background studies. The details can be found in the proceedings of the 1999 Workshop on Standard Model physics at the LHC [18], except where mentioned.

3.1 $\sin 2\beta$ from $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{S}$ and $\mathrm{B} \to \phi \mathrm{K}^0_\mathrm{S}$

The $\mathrm{B} \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{S}$ decay is the benchmark channel for the B factories running at the $\Upsilon(4S)$. Scaling the present precision using the expected integrated luminosity by 2006 one can assume that the precision on $\sin 2\beta$ will be about 0.03 at the start of the LHC.

Yet the huge statistics of the LHC and the precision of the LHCb detector can bring new insights to this channel. The general form of the CP asymmetry is

$$A_{\mathrm{CP}}(t) = A_{\mathrm{dir}} \cos(\Delta m t) + A_{\mathrm{mix}} \sin(\Delta m t) \tag{1}$$

where A_{dir} is the direct violation (expected to be very small in the SM) and $A_{\mathrm{mix}} = \phi^{\mathrm{B_d}}_{\mathrm{mix}}$ the mixing induced CP violation, equal to $\sin 2\beta$ in the SM. LHCb expects to reconstruct and tag $\sim 10^5$ events per year with a mass and flight time resolution of 7 MeV and 36 fs [10]. After one year of data taking the three LHC experiments (ATLAS, CMS, LHCb) will reach a combined precision of 0.011 on A_{mix} and A_{dir}.

LHCb is presently also studying the related channel $\mathrm{B} \to \phi \mathrm{K}^0_\mathrm{S}$ that is experimentally more challenging. In this decay the CP violation follows the same equations as for the previous, but arises via penguin loops. A different $\sin 2\beta$ measurement from this channel would be an indirect evidence of physics beyond the Standard Model.

3.2 $\sin 2\delta\gamma$ from $\mathrm{B_s} \to \mathrm{J}/\psi\phi$

The $\mathrm{B_s} \to \mathrm{J}/\psi\phi$ decay is the strange counterpart of the the $\mathrm{B_d} \to \mathrm{J}/\psi \mathrm{K}^0_\mathrm{S}$ decay. It is thus sensitive to the mixing phase $\phi^{\mathrm{B_s}}_{\mathrm{mix}} = -2\delta\gamma$. There are two essential differences. The first is that unlike $\sin 2\beta$ that is known to be large, $2\delta\gamma$ is expected to be very small in the SM. The other is that since both the ϕ and the J/ψ are vector meson, two orbital momentum states can occur, which requires an angular analysis. LHCb expects to reconstruct and tag 80k events per year with a proper time resolution of 31 fs [19]. The expected resolution on $\delta\gamma$ is about 2° (depending on x_s) after one year of running. This would allow to set an upper limit on $\delta\gamma$ as it is expected to be smaller.

The related channel $\mathrm{B_s} \to \mathrm{J}/\psi\eta$ has a well-defined orbital momentum and is thus easier to analyze. On the other hand it is experimentally more challenging as the final state contains two γ. This channel is under study.

3.3 α from $\mathrm{B} \to \pi\pi$ and $\mathrm{B} \to \rho\pi$

The CP asymmetry in $\mathrm{B} \to \pi\pi$ decays is governed by the CKM angle α. LHCb expects to reconstruct and tag $\sim$ 5k events per year in this decay mode, which will be about an order of magnitude more than what is expected from B factories. The selection of this channel relies on the K/π separation power of the RICH detectors to remove backgrounds as $\mathrm{B} \to \mathrm{K}\pi$ [9].

However, the extraction of the α angle from the measurement of the CP asymmetry is not straightforward as the tree decay amplitude is accompanied by a sizable but unknown penguin decay amplitude. This has the effect of diluting

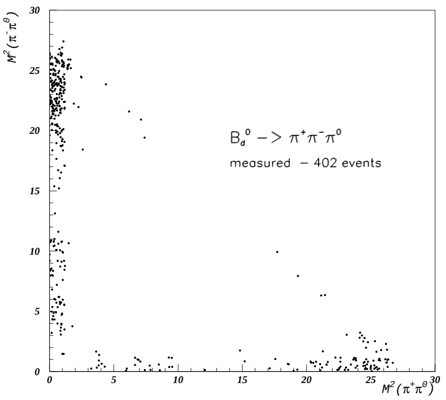

Fig. 2. The Dalitz plot of the B → $\pi\pi\pi$ decay. The three interference regions are well visible.

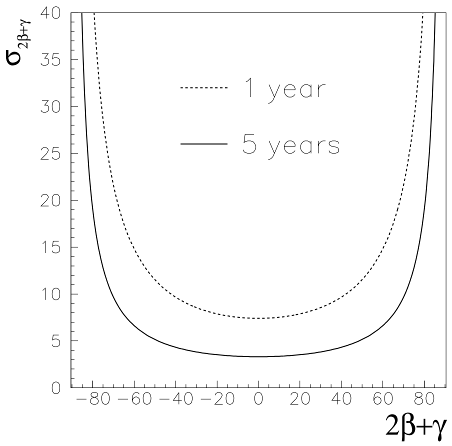

Fig. 3. Error on γ versus $2\beta+\gamma$ using the channel $\mathrm{B} \to \mathrm{D}^*\pi$.

the CP asymmetry by an unknown factor. The penguin fraction can in principle be recovered from a detailed analysis of the $\mathrm{B_{s,d}} \to \mathrm{K}\pi$ decay; but this has still to be studied from the experimental side.

The $\mathrm{B} \to \rho\pi$ decay mode on the contrary has the advantage of a higher branching ratio and of providing enough observables to extract all strong and weak phases. On the other hand the final state contains a π^0 which significantly reduces the expected yield compared to the two-body channel. In total $\sim$ 1.3k events per year will be reconstructed and tagged. Because of the π^0 the mass resolution is only 35 MeV in this channel. Figure 2 shows the three ρ interference regions in the Dalitz plot of the $\pi\pi\pi$ final state. There has been a significant improvement since the 1999 Workshop [18]: the lower left corner of the Dalitz plot is now also visible thanks to the new π^0 trigger that has been implemented in the algorithm of the electromagnetic first level trigger [8]. In the other corners of the triangle most of the energy is taken by a charged pion and the decay is thus triggered by the hadron trigger.

The expected precision on α depends on α and strong phases and lies in the range 3°–5°.

3.4 $\gamma + 2\beta$ from $\mathrm{B} \to \mathrm{D}^*\pi$

The combined time-dependent analysis of the four decays $(\mathrm{B_d}, \overline{\mathrm{B_d}}) \to \mathrm{D}^{*+}\pi^-$ and $(\mathrm{B_d}, \overline{\mathrm{B_d}}) \to \mathrm{D}^{*-}\pi^+$ is sensitive to the CKM phase $\gamma + \phi_{\mathrm{mix}}^{\mathrm{B_d}}$. Assuming a precise measurement of $\phi_{\mathrm{mix}}^{\mathrm{B_d}} = 2\beta$ from $\mathrm{B} \to \mathrm{J}/\psi\mathrm{K_S^0}$ this channel measures γ in a theoretically clean way. As one of the tree decay channels is doubly Cabibbo-suppressed, the two asymmetries are expected to be small, which calls for very large statistics. The $\mathrm{B} \to \mathrm{D}^*(\mathrm{D}(\mathrm{K}\pi)\pi)\pi$ decay chain yields 73k reconstructed and tagged events per year, which is insufficient for a precise determination of γ. Additional 460k events can be recovered allowing the D to decay inclusively to any final state containing two charged tracks. The very precise vertex locator system allows to recover the dynamics of the system using the direction of the D meson [20]. Finally the $B \to D^* a_1$ decay is also considered and yields 360k events per year. An angular analysis (not done yet) is needed to use these events; they are thus not used in the following results. The triggering of all these high multiplicity hadronic decay channels relies on the hadron trigger.

The final precision on γ depends on strong phases and $\gamma + 2\beta$. It is shown in Figure 3 for a vanishing strong phase difference. A non-zero strong phase difference shift the curves laterally. In the optimal situation where $\gamma + 2\beta + \Delta_{\text{strong}} \approx 0$ the precision on γ is about 7° after one year [20].

3.5 $\gamma - 2\delta\gamma$ from $B_s \to D_s K$

The $B_s \to D_s K$ decay is the strange counterpart of the $B \to D^* \pi$ decay described above and is thus sensitive to $\gamma + \phi^{B_s}_{\text{mix}}$. The mixing phase is $\phi^{B_s}_{\text{mix}} = -2\delta\gamma$ in the SM and can be measured using the $B_s \to J/\psi\phi$ decay.

On the contrary of $B \to D^* \pi$, the CP asymmetry is expected to be large in this channel. We expect to reconstruct and tag 2100 $B_s \to D_s^-(KK\pi)K^+$ and 320 $B_s \to D_s^+(KK\pi)K^-$ per year. The identification of this signal needs the RICH (to reduce the $B_s \to D_s\pi$ background) and the hadron trigger. The B mass resolution of 11 MeV is also of great help to improve the signal to background ratio. The proper flight time resolution — that is of great importance for time-dependent B_s decay analyses — is 43 fs.

As for the previous decay the precision on γ depends on $\gamma + \phi^{B_s}_{\text{mix}} + \Delta_{\text{strong}}$, but also on the B_s oscillation frequency x_s. The overall resolution on γ is of the same order as in the $B \to D^* \pi$ channel.

3.6 $|V_{td}|/|V_{ts}|$ from Δm_s

The flavour-specific $B_s \to D_s\pi$ decay is the best candidate to measure the Δm_s mass difference of the B_s system. If it is not too large the oscillations will probably have been observed at the Tevatron. The LHC will allow to cover a much higher Δm_s range.

LHCb expects 34k reconstructed and tagged $B_s \to D_s\pi$ decays per year. The time resolution is 43 fs. The expected significance of the measurement versus Δm_s is shown in Figure 4 for one year of data taking. A 5σ measurement is possible for $\Delta m_s < 48\ \text{ps}^{-1}$. Assuming Δm_s is in this range one can extract the CKM matrix element ratio $|V_{td}|/|V_{ts}|$ by

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d}}{m_{B_s}} \xi^2 \frac{|V_{td}|^2}{|V_{ts}|^2} \tag{2}$$

and thus $|V_{td}|$, which is related to the length of the side opposite to the angle γ in the CKM unitarity triangle (see Fig. 1). This method is affected by a theoretical uncertainty of about 5% on the hadronic form factor ratio ξ. Hopefully this will decrease by 2006.

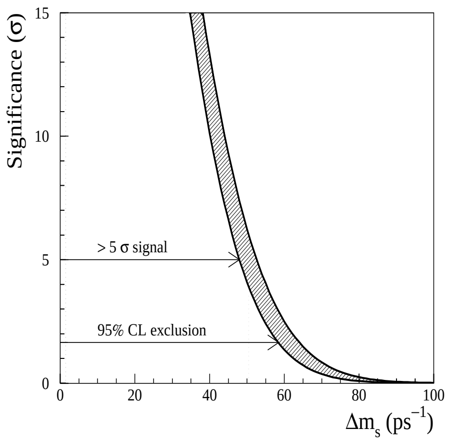

Fig. 4. Significance of the Δm_s measurement versus Δm_s.

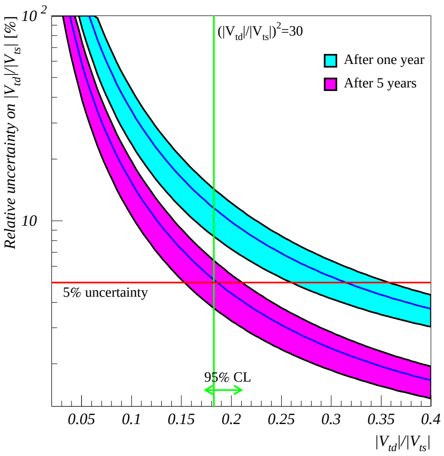

Fig. 5. Error on $|V_\mathrm{td}|/|V_\mathrm{ts}|$ in % versus $|V_\mathrm{td}|/|V_\mathrm{ts}|$ using the channel $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{d,s}$.

3.7 $|V_\mathrm{td}|/|V_\mathrm{ts}|$ from $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{d,s}$

The flavour changing neutral current decay $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{s}$ is of great interest because of its sensitivity to new physics via loops and penguins. It also allows to extract the $|V_\mathrm{td}|/|V_\mathrm{ts}|$ ratio using in addition the Cabibbo-suppressed decay $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{d}$. Only inclusive measurements are not affected by large form-factor related uncertainties and can be used to get a clean extraction of the CKM matrix elements. Ref. [21] advocates the use of the partially integrated branching ratio

$$\frac{|V_\mathrm{td}|^2}{|V_\mathrm{ts}|^2} = \frac{\int\limits_{s_\mathrm{min}}^{s_\mathrm{max}} \mathrm{d}s \frac{\mathrm{dBR}(\mathrm{B}\to\mu\mu\mathrm{X}_\mathrm{d})}{\mathrm{d}s}}{\int\limits_{s_\mathrm{min}}^{s_\mathrm{max}} \mathrm{d}s \frac{\mathrm{dBR}(\mathrm{B}\to\mu\mu\mathrm{X}_\mathrm{s})}{\mathrm{d}s}} \tag{3}$$

where s is the squared dimuon mass and the integration limits are chosen to be far away from any hadronic source of dimuons

$$s_\mathrm{min} = 1\ \mathrm{GeV}^2 \quad \text{and} \quad s_\mathrm{max} = 6\ \mathrm{GeV}^2. \tag{4}$$

The theoretical uncertainty on the above defined ratio is less than 1% which makes this method potentially more precise than the one presented in Eq. (2).

LHCb expects 25k $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{s}$ and 500 $\mathrm{B} \to \mu\mu\mathrm{X}_\mathrm{d}$ (assuming $|V_\mathrm{td}|^2/|V_\mathrm{ts}|^2 = 1/30$) accepting all final states with up to two kaons ($\mathrm{K}^\pm$ and K^0_S) and up to four charged pions [22, 23]. To recover the whole inclusive spectrum the final states are weighted by a factor depending on the detection efficiency and isospin considerations.

Figure 5 shows the expected relative error on $|V_\mathrm{td}|/|V_\mathrm{ts}|$ versus $|V_\mathrm{td}|/|V_\mathrm{ts}|$ for one and five years of data taking. The $> 32\%$ C.L. range for this ratio using the presently available data [24] is shown. We expect a precision on $|V_\mathrm{td}|/|V_\mathrm{ts}|$

Parameter	channel	HT	RICH	yield	Precision
β	$\mathrm{B_d} \to \mathrm{J}/\psi \mathrm{K^0_S}$			100k	$\sigma(\sin 2\beta) = 0.02$
	$\mathrm{B_d} \to \phi \mathrm{K^0_S}$	HT	RICH	To be studied	
α	$\mathrm{B_d} \to \pi\pi$	HT	RICH	4.9k	depends on theory
	$\mathrm{B_d} \to \rho\pi$	HT		1.3k	$2.5^\circ < \sigma(\alpha) < 5.0^\circ$
γ	$\mathrm{B_d} \to \mathrm{D}^*\pi$	HT	RICH	530k	$\sigma(\gamma) \approx 10^\circ$
	$\mathrm{B_s} \to \mathrm{D_s K}$	HT	RICH	2.4k	$\sigma(\gamma) \approx 10^\circ$
$\delta\gamma$	$\mathrm{B_s} \to \mathrm{J}/\psi\phi$			80k	$\sigma(\delta\gamma) \approx 2^\circ$
	$\mathrm{B_d} \to \mathrm{J}/\psi\eta$			To be studied	
$\lvert V_\mathrm{td}/V_\mathrm{ts}\rvert$	$\mathrm{B_s} \to \mathrm{D_s}\pi$	HT		34k	$\sigma(\Delta m_\mathrm{s}) \approx 0.01\ \mathrm{ps}^{-1}$
	$\mathrm{B_d} \to \mu\mu \mathrm{X_{s,d}}$		RICH	20k	$\sigma(\lvert V_\mathrm{td}/V_\mathrm{ts}\rvert) \approx 10\%$

Table 1. Summary of the channels mentioned in the text. The annual number of triggered, reconstructed and tagged (when needed) events and the precision on the physics parameters are given. The channels that need the RICH and the hadron trigger (HT) are especially mentioned.

of about 10% after one year depending on $|V_\mathrm{td}|/|V_\mathrm{ts}|$. The Δm_s method being limited by theoretical uncertainties, the ratio extracted this way becomes more precise after a few years of data taking.

4 Conclusion

The LHCb experiment allows a precise determination of the CKM unitarity triangle. In this brief overview we have shown how LHCb can measure five parameters in two ways each. Table 1 summarizes all expected yields. This allows to over-constrain the model and may thus reveal New Physics.

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